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CCS infrastructure development scenarios for the integrated Iberian Peninsula and Morocco energy system

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Abstract

This paper briefly illustrates a method to represent national energy systems and the geographical details of CCS infrastructures in the same technical-economic model. In the MARKAL-TIMES modeling framework a model of Morocco, Portugal and Spain with both spatial and temporal details has been implemented. As a function of assumptions on the development to 2050 of mitigation levels, economic growth and CO_2 capture-transport storage characteristics, dozens of scenarios were prepared with the TIMES-COMET model. A few results on optimal levels of CCS contribution to mitigation compared to other energy system options are presented. The results also indicate the least cost lay out of the main capture, transport and storage infrastructures. It is concluded that the availability of CCS after 2020 will reduce the cost of mitigation in the Iberian Peninsula as soon as the EU GHG emissions reduction targets become more stringent than decided so far.

Keywords: Energy scenarios; climate change mitigation; CO_2 emissions; capture transport storage infrastructures; MARKAL-TIMES; partial economic equilibrium; bottom-up technological models; GIS transport models

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Introduction

Important international organizations call for a global 'energy revolution' [1] [2] and a stronger commitment to mitigate climate changes [3]. When preparing a better energy system for the future, policy and decision makers in the field of energy often need to understand not only what technology options best satisfy their objectives under changing external conditions and when, but also where the big infrastructures that implement those options can be optimally located.

The CO_2 Capture and Storage technology (CCS) can contribute significantly to reduce the amount of CO_2 injected in the atmosphere by power plants and other large energy intensive industrial sectors in the medium term. When commercially available the CCS technology will be deployed 'close' to geological formations suitable to permanently store CO_2. In order to understand its market potential, CCS has to be analysed in relation to at least two systems: the national energy systems which will emit CO_2 and the territory where physically CO_2 has to be captured, transported and permanently stored.

Important CCS related policy questions are:

- How does CCS depend on the level of mitigation demanded by the climate scientists and possibly agreed by future mitigation protocols?
- How does the potential CCS market depend on national economic growths?
- What is the role of CCS compared to other energy system related mitigation options?
- How sensitive is the cost, the potential and the overall role of CCS to the geological conditions and CO_2 injection processes knowledge?
- How does the potential and cost of CCS depend on socio-political factors, such as the acceptance of different pipeline networks or the possibility to export / import CO_2 across countries?

This paper presents results of a study aimed to provide spatial and temporal elements to the assessment of CCS in the West Mediterranean. Section 2 summarizes elements of the model and its input. Section 3 presents the main scenario assumptions. Section 4 exemplifies the results both at the geographical level and national energy system developments level. Some evidence of the study is summarized in the conclusion.

Methodology and models

Top-down, hybrid, and bottom-up approaches are used to support policy and decision makers in long term energy and climate change mitigation related issues [4] [5]. The bottom-up approach, possibly in its hybrid variant, seems by far more appropriate than the former to analyse energy related problems with high degree of technological and infrastructural details related to both spatial and temporal issues.

The present study used a systems analytical approach based on bottom-up technical-economic models generated by the MARKAL-TIMES software and geographical information system (GIS). The approach develops the methodology used in [6, 7], and was chosen to integrate spatial, temporal, as well as techno economic aspects to determine the role of CCS in the energy system and the development of the CCS infrastructure. Other studies have also assessed CCS infrastructures, but not in this integrated manner.

The new TIMES-COMET model integrates the national TIMES models of Morocco, Portugal and Spain to the new TIMES-CCS model of the West Mediterranean [8]. In this new hard-linked model, which is a hybrid energy-transport model with half a million variables and equations, country regions and capture/storage sub-regions interact in several ways in order to meet the GHG emission reduction targets. If unfavourable geographical or geological conditions make the cost of capture transport and storage too high, the regional models reduce emissions increasing the use of other mitigation options. If the sub-regions demand so much energy from the country regions that CCS costs become too high, the energy supply mix of the country regions changes. In the sectors where the capture of CO_2 is most expensive in the sub-regions, the country regions tend to use more efficient technologies or switch fuels.

Inputs to this hybrid energy-transport model are:

- A database with the technical characteristics and geographical location of CO_2 sources which on average emitted more than 0.1 Mt CO_2/a (or close to it) in the period 2005-9 in Morocco, Portugal and Spain (almost 300, with a total emission of about 150 Mt CO_2 in 2009); for each emission point, the sector (Electricity, Refineries, Iron and Steel, Cement, Glass, Pulp and Paper, Other Industries), and the main energy carrier (Biomass, Coal, Natural Gas, Oil, Waste) are specified [9, 10];
- A database with the techno-economic characteristics and geographical location of about 160 geological formations in Morocco, Portugal and Spain, where significant amount of CO_2 can be permanently stored; a potential of 7.7 Gt CO_2 in Portugal, 23 Gt CO_2 in Spain (with an onshore sink potential of around 75% of the total Iberian potential), and 0.4 Gt CO_2 in Morocco were estimated [11];
- A set of areas, where all emission sources are aggregated in 45 emission clusters and storage formations are aggregated in 29 sink clusters [12]; furthermore, 23 sources and 14 sinks were included in the model, but not included in any cluster, since they were too distant from other sources or sinks; for consistency, those isolated sources and sinks were numbered and dealt with in the same manner as the clusters, and any considerations made hereafter also apply to them;
- The distances among all clusters – emission clusters to emission clusters, emission clusters to sink clusters – calculated in a Geographical Information System (GIS) – and their cost, estimated with the appropriate terrain factors ('relative cost variation with respect to standard cost'), as dependent on the diameter (and the maximum possible annual CO_2 flow) [13];
- The technical economic characteristics of CCS related technologies – capture, compression, transport, and injection in the sink [14-19] (Table 1) and of competing mitigation options (Table 2); and
- New energy systems analyses of Morocco, Portugal and Spain [20, 21, 22], updated versions of the TIMES-PT [23] and TIMES-ES [24] models extracted from the Pan European TIMES model (PET) [25], plus a new TIMES-Morocco model [26].

The new model provides possible long term developments of the Moroccan, Portuguese and Spanish energy systems by scenario, assesses the role of CCS in the national portfolio of mitigation measures

Table 1: Characteristics of the CO_2 capture technologies in the model

Sector	Fuel group	Capture Rate, %	ELC in GJ/tCO_2	Fuel in GJ/tCO_2	Investment costs [M€2007/(ktCO_2/a captured)] 2020	2030	2040	2050
ELE	COA	90		2.7	0.141	0.139	0.121	0.105
ELE	ǂ COA	90		3.3	0.162	0.148	0.130	0.094
CEM	any	85	0.7	4.4	0.175	0.175	0.175	0.175
GLS	any	90	1.3	4.7	0.132	0.132	0.132	0.132
IIS [a]	any	65	1.2	4.5	0.032	0.032	0.032	0.032
IOI	any	90	1.3	4.7	0.132	0.132	0.132	0.132
PnP	any	90	1.1	3.6	0.092	0.092	0.092	0.092
REF	any	85		2.9	0.233	0.233	0.233	0.233

a: blast furnaces with CCS consume less coke (-4.9 GJ/kt CO_2); this amount was not modelled; however this approximation is not likely to influence the main results; fuel input of power plants reduces in 2050 to 1.4 for coal, 2.0 for gas; lifetime=30 years; fixed O&M is 5% of the investment cost; learning goes with an assumption of doubling the cumulative production each 4 years; industrial sectors: CEM=Cement plant, ELE= Power, heat, CHP plants, GLS=Glass, IIS= Iron & Steel, IOI= Other Industry, PnP= Pulp & Paper, REF=Oil Refineries.

Table 2: Investment costs of fossil power plants with/out CCS and solar/wind options add efficiencies

Investment cost (in €'2005/kWp)		2010	2020	2035	2050
Pulverised coal power plant, new	---		1250		1000
	with CCS		2100		1500
Natural gas combined cycle, new	---		530		470
	with CCS		1000		700
PV Roof panel.SOL.New	EUPVSOL101	3600		1000	
PV Plant Size.SOL.New	EUPVSOL201	2655		727	
Solar Thermal.SOL.New (CSP)	EUTHSOL101	3360		2500	
Wind Offshore 2.New	EUWINOF201	1650		1370	
Wind Onshore 2.New.	EUWINON201	1000		950	

The availability of solar PV plants grows from 32% in 2010 to 35% in 2030, CSP from 25% ot 35%, wind onshore in the range 30-32%, wind offshore 50%; fixed O&M around 4% for wind and 2% for solar; lifetime 20 years for wind, 25 for solar.

under several scenario assumptions, and for each scenario builds cost effective CO_2 source-transport-sinks combinations in GIS format.

Development drivers and Scenarios

All the scenarios built with the TIMES-COMET model take into account the same technological developments, CCS technologies learning curves, CO_2 unit transport costs, and policies of the whole energy sector. In order to assess the main CCS related policy questions outlined in the introduction, the following scenario drivers have been chosen and are varied, in general aspects (set 1):

- Economic growth,
- National mitigation level,
- CCS availability,

and in CO_2 transport and storage infrastructure aspects (set 2):

- Storage capacities,
- National CO_2 pipeline networks, and
- Possibility to transport across country borders.

Two economic developments have been assumed for Portugal and Spain. The high GDP growth (HD) assumes that the economy grows in forty years in Spain by 158% (2.4%pa) and in Portugal by 123% (2.0%pa). The low GDP growth (LD) assumes that the economy grows in forty years in Spain by 58 % (1.1%pa) and in Portugal by 43% (0.9%pa). Only one GDP growth has been assumed for Morocco, namely 314% in the period 2010-2050 (3.6%pa). The 68 demands for energy services develop differently by sector and use, at a weighted average of 1.7%pa (per annum) in the high demand case in the three countries together, much less than the average growth of the GDP, equivalent of about 2.5%pa.

Compared to the 2005 CO_2 emissions from energy systems and industrial processes – namely 460 Mt CO_2 in Portugal and Spain together – three emission reduction levels to 2050 where analyzed:

- -20%, meaning that the emissions are kept constant after 2020, at the level prescribed by the EU,
- -40% (linearly interpolated), and
- -80% (linearly interpolated), the target of rich countries if the temperature increase is kept below 3ºC [3].

Table 3: 2005 CO_2 emissions by country and concentration level / capture potential

		CO_2 emissions in 2005	Morocco	Portugal	Spain
		TOTAL (Mt CO_2/a)	37	77	381
Can be captured (sources >0.1 Mt CO_2/a)			57%	38%	30%
Cannot be captured:	other ETS (sources <0.1 Mt CO_2/a)		0%	21%	25%
	other industrial sectors No-ETS		0%	6%	7%
	Agriculture, Commercial, Residential, Transport		43%	35%	38%

ETS=European Emission Trading System sectors; other Non-ETS indicate industrial sectors where the ETS is not applicable

Also 0% reduction cases were run for comparison. Morocco has no commitments till 2050, but can sell permits to Spain and Portugal up to 20% of their mitigation commitments. Spain and Portugal can buy permits from the Rest of the Word (RoW), at prices increasing from 50€'2005/t CO_2 in 2020 to the following prices in 2050: 150 in the -20% cases, 350 in the -40% cases and 500 in the -80% cases.

In some scenarios CCS is not available (NO CCS), in all the others it is. CCS is applicable only to sources emitting more than 0.1 Mt CO_2/a. Based upon a detailed study of emission inventories in the 2005-10, only 30-40% of total Portuguese / Spanish emissions can be captured now (Table 3).

Each storage point is characterized by the investment and corresponding fixed operating and maintenance costs, the maximum yearly injection rates and cumulative capacity of the geological formations. All these parameters are estimated taking into account the type of geological formation, its depth, its porosity, dimensions, thickness, etc. The resulting cost – cumulative capacity graph, in the two alternative geological model assumptions (HIGH, LOW), is reported in Figure 1. In this case study, the cumulative amount stored in 40 years is 14% of the permanent storage capacity in ES+MO+PT, mainly available in Spain, and the maximum annual flow does not exceed 50% of the annual injection capacity.

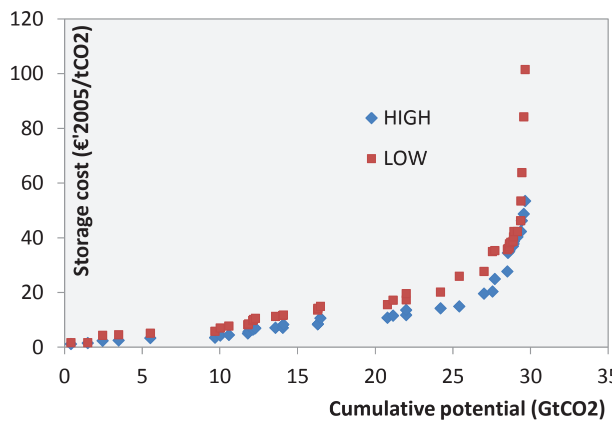

Figure 1: Cumulative storage cost curve in ES+MO+PT

The information about CO_2 transport network is embodied in eligible pipelines connecting capture sub-regions to storage sub-regions, as well as capture to capture sub-regions and storage to storage sub-regions. Two drivers represent possible layouts of the pipeline network. The first one refers to degrees of freedom in the design of the pipeline network in each country: whether it has to follow existing pipeline networks where available, mainly the natural gas transports system (GAS), or not (FREE). In the free case the 78 emission clusters can send CO_2 to the 43 storage clusters using more than 3000 routes, in the case following the gas network only 200 routes are permitted. The second driver refers to the possibility of moving CO_2 flows from one country to another (REGional) or to restrict CO_2 movements inside each country (NATional).

About half of the 72 drivers' combinations have been run with the TIMES-COMET model. The study concentrated on a central scenario (CONSERVATIVE CCS) and 6 variant scenarios: they illustrate the

Table 4: Scenarios definition

DESCRIPTIVE NAME	CODE	GDP Growth	Mitigation level	Storage Potential	National Routes	Cross-Frontier
Set 1: Emission side						
CONSERVATIVE CCS	HD.40-GAS.NAT.LS	HIGH	40%	LOW	GAS	NAT
HIGH MITIGATION	HD.80-GAS.NAT.LS	HIGH	80%	LOW	GAS	NAT
NO-CCS	HD.40-No.CCS	HIGH	40%-NO CCS	-	-	-
LOW ECONOMIC GROWTH and HIGH MITIGATION	LD.80-GAS.NAT.LS	LOW	80%	LOW	GAS	NAT
Set 2: Transport and storage infrastructures side						
CONSERVATIVE CCS	HD.40-GAS.NAT.LS	HIGH	40%	LOW	GAS	NAT
CROSS-FRONTIER PIPELINES	HD.40-GAS.REG.LS	HIGH	40%	LOW	GAS	REG
FREE ROUTES	HD.40-FREE.NAT.LS	HIGH	40%	LOW	FREE	NAT
OPTIMISTIC STORAGE	HD.40-GAS.NAT.HS	HIGH	40%	HIGH	GAS	NAT

effect of changing with respect to the central scenario a single driver – two in the low economic growth case for having comparable CCS contributions (Table 4). For each scenario the model:

- calculates optimal long term developments of the Moroccan, Portuguese and Spanish energy systems, mainly final energy consumption, primary energy supply, electricity generation, CO_2 emissions and the optimal technology mix;
- assesses the role of CCS in the national portfolio of mitigation measures; and
- builds cost effective CO_2 source-transport-sinks combinations.

Results

When available, CCS contributes considerably to mitigation. In 2050 in the CONSERVATIVE CCS scenario it captures about 30% and avoids 25% of the emissions in Portugal and Spain, 33% and 28% respectively in the High Mitigation scenario (Figure 2, up, left). More than 90% of the CO_2 emitted by concentrated sources is captured. Furthermore CCS can contribute considerably to lower the cost of mitigation, if in the future the EC decides to reduce emissions more than 20% after 2020. According to the TIMES-COMET model in the high demand scenarios, reducing CO_2 emissions in Portugal and Spain in 2050 by 40% increases the total discounted system cost by 0.5% compared to the base level of -20%; the cost increase is 3.0% if emissions are reduced by 80%. If CCS is not available, the cost of mitigation increases to 1.1% and 4.5% respectively.

In the CONSERVATIVE CCS scenario in 2050, CCS avoids 103 Mt CO_2 in Spain, 14 Mt CO_2 in Portugal. Summing the emissions produced by the capture processes, 133 Mt CO_2 are captured in Spain and 17 in Portugal. The TIMES-COMET model calculates these amounts based on the costs of capture in 66 emission clusters, transport over the Iberian Peninsula and storage in 40 sink clusters, and its comparison to the cost of all the mitigation options represented in the national energy systems.

At the sectoral level, capture from power plants becomes competitive below 50€/t CO_2 captured, from iron & steel and pulp & paper plants below 75 €'2005/t CO_2 captured, from refineries and cement plants below 100 €'2005/t CO_2 captured, from glass plants and other industries below 125 €'2005/t CO_2

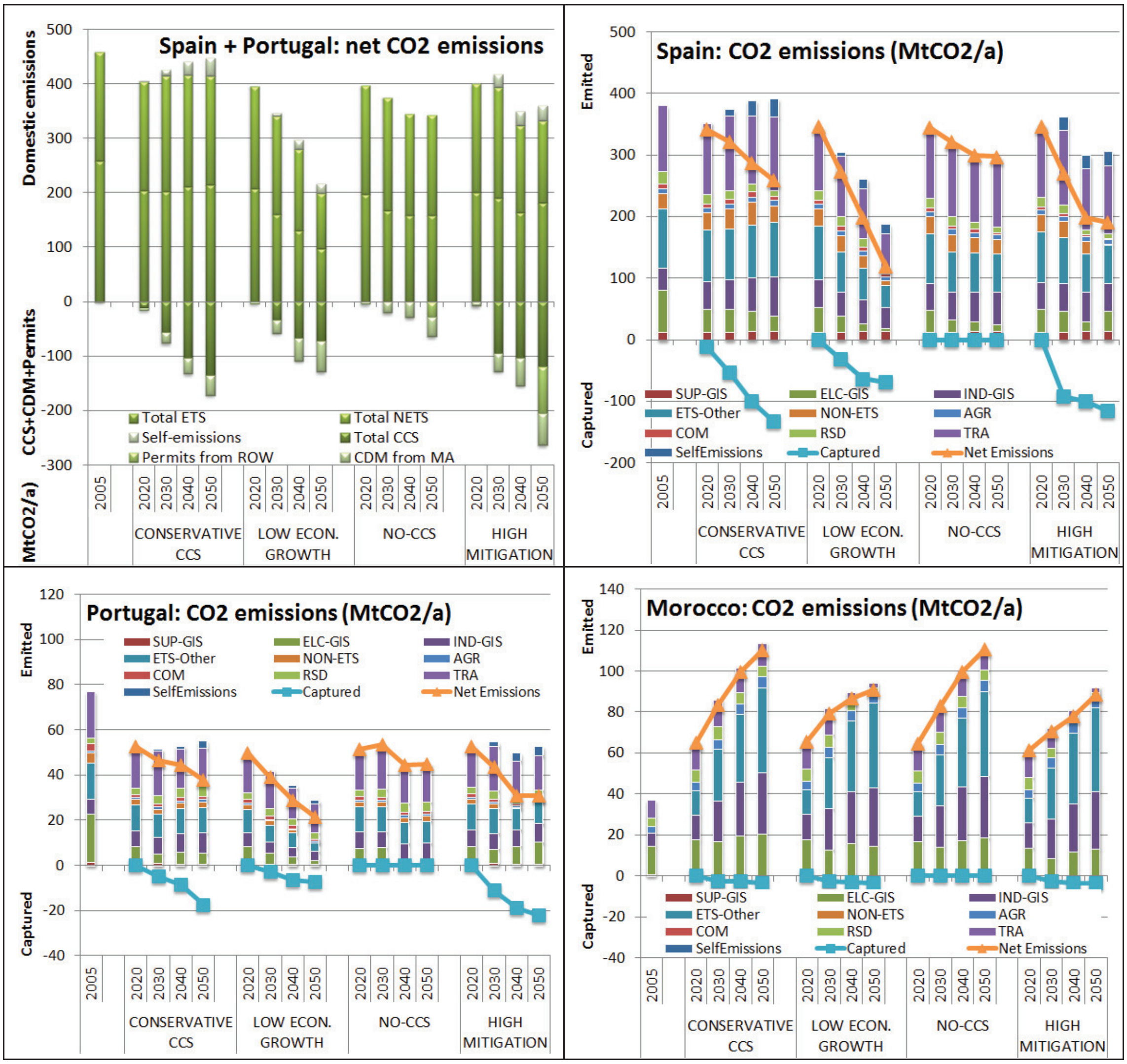

Figure 2: CO_2 emissions of Spain, Portugal and Morocco by scenario

captured. Combining the industrial structure in the Iberian Peninsula with the competitiveness of the seven different capture processes, in the central scenarios the contribution to CCS of cement is quite stable around 40%, refinery just below 15%, iron & steel just above 10%, other industries 6%, pulp & paper above 3%, glass below 2%. The role of electricity strongly depends on the scenario: at low mitigation levels it captures more than two third of the total, it reduces its contribution to 25% in the central scenario and reduces its contribution below 20% in the most demanding scenarios. This is due to fact that the power sector has many more mitigation options then the other industrial sectors.

As a result of the location by sector and the mitigation effort, the highest amount of CO_2 in the central scenarios is captured in the following areas (Figure 3, left): Aboño (C02) and Barcelona (C11) above 10 Mt CO_2/a, La Mancha (C05), Huelva (C20), Gibraltar (C22), Euskadi (C24), Tarragona (C27), Valencia

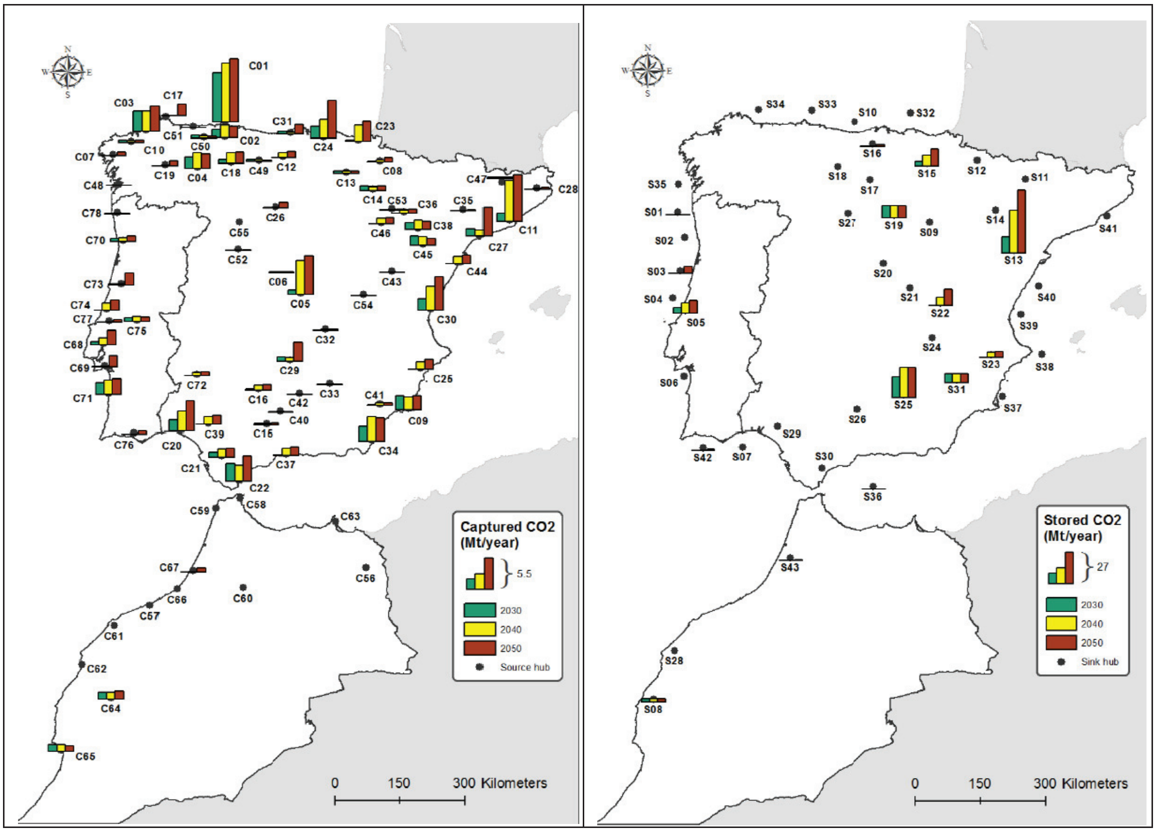

Figure 3: Capture (left) and storage by cluster and year in the CONSERVATIVE CCS scenario

(C30), Almeria (C34) in Spain and Sines (C71) in Portugal above 5 Mt CO_2/a, Cartagena (C09), Navarra (C23) Puertollano (C29) in Spain, Lisbon C(68) and Coimbra (C73) in Portugal above 3 Mt CO_2/a.

Taking account of cumulative and annual capacities, cost and proximity to emission sources, only 8 out of 40 sink clusters in the Iberian Peninsula are used by the model to permanently store significant amount of CO_2 in most scenarios (Figure 3, right): Logroño (S15), Úbeda (S25), Alcañiz (S13), Cuenca (S22), Almansa (S23), Moratalla (S31), and Aranda de Duero (S19) in Spain in decreasing order of importance, and Lusitanian Onshore (S05) in Portugal. S25 is very competitive, but is limited by both annual and cumulative capacity. S19 and S31 are competitive but limited by the cumulative capacity. S05 is limited by the annual capacity. Given their potential and cost, sinks located in Spain dominate the storage activity of both domestic CO_2 and CO_2 from Portugal and Morocco.

The non-availability of cross-boundary pipelines, representing a political preference mentioned by several stakeholders [27], results in more domestic storage in the Portuguese and the Mediterranean sea for Morocco. No impact on the energy system and mitigation options implemented in Spain is observed. In other words, cross-boundary pipelines may make a difference in terms of the interests and priority given to exploration and research related to storage potentials in the countries, especially in Spain.

In the FREE ROUTES scenario many more routes are possible to transport CO_2 from sources to sinks. In fact, as shown in Figure 4, the theoretical optimum suggests to use many more pipelines. But the advantage over the more realistic scenario that forces the CO_2 pipeline to run parallel to existing gas pipelines, is negligible in terms of both amount stored (<2%) and total system cost (<<0.1%).

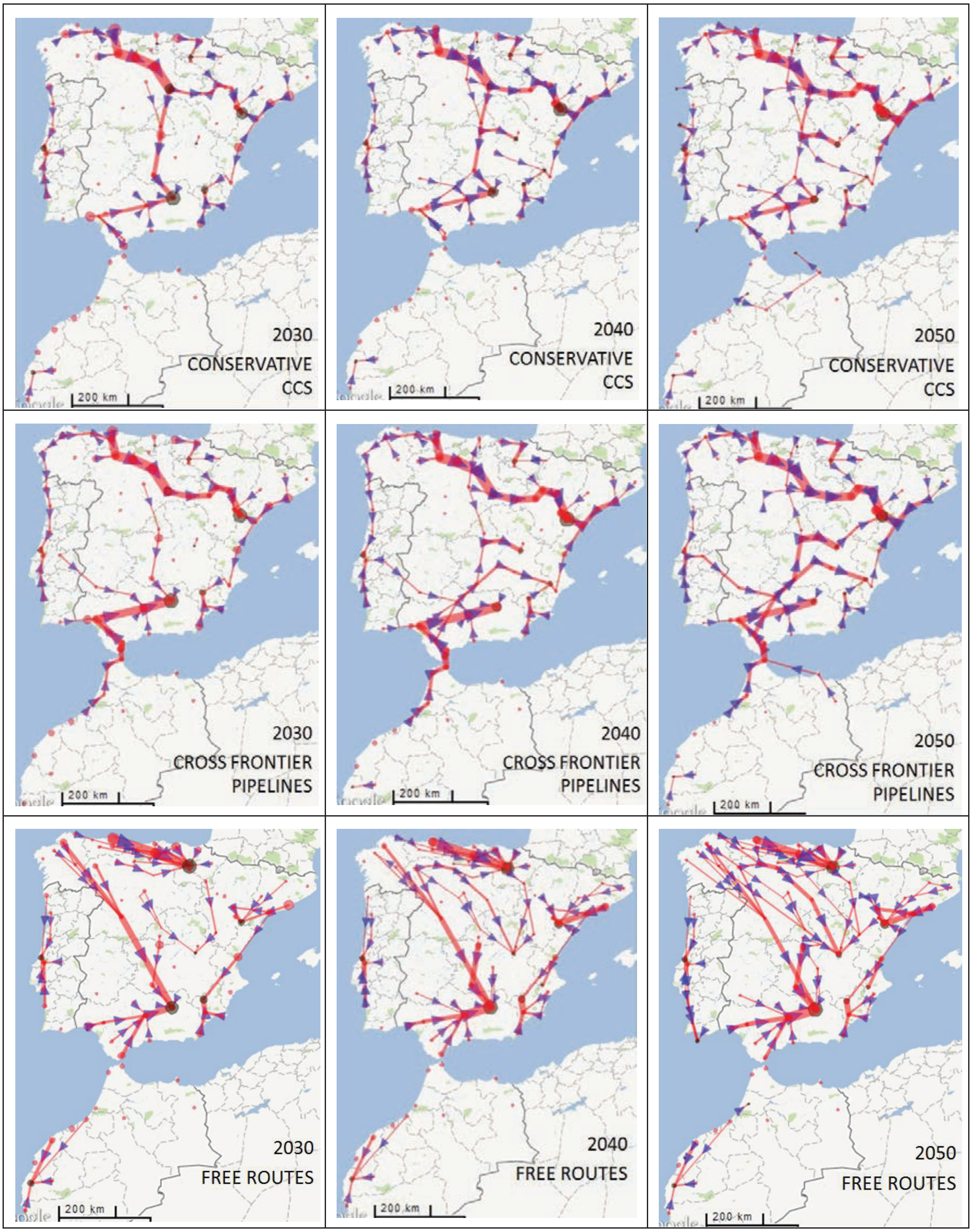

Figure 4: Optimal development of the CCS transport network by scenario and year [28]

As regards Morocco, the focus of the analysis is the contribution of the country to the mitigation obligations of Spain and Portugal, as permitted in the scenarios in order to represent the CDM opportunities. CCS appears as a possible mitigation option selected by the model under the conditions modelled in the exercise. The recent acceptation at the international level of CCS in the CDM framework would make possible such a strategy. Since only a small part of the CO_2 captured in Morocco can be stored in the country, sending CO_2 across the border is a precondition to the use of CCS in Morocco, the rest being sequestrated in Spain. This may contribute to the acceptability of CCS in Morocco. If sending CO_2 to Spain is not permitted, buying CDM permits from Morocco remain of interest for Spain and Portugal (Figure 2, left, up), but the corresponding projects in Morocco are different: investments in CCS are decreased and compensated by investments in gas and solar power plants, both resulting also in emission reductions compared to unrestricted scenario in Morocco.

The development of the CCS infrastructures over the years and the 'robust' infrastructures across scenarios, can be a guide to identify the location of the most interesting CCS infrastructures, those for which detailed feasibility studies open the possibility to implement commercial projects. Examples are: in the north east of Spain from C23 (Navarra) to S15 (Logroño), in the east of Spain from C11 (Barcelona) to S13 (Alcañiz), in the south of Spain from C20 (Huelva) and C22 (Gibraltar) to S25 (Úbeda), and in Portugal from C71 (Sines) and C73 (Coimbra) to S05 (Lusitanian onshore).

A good indicator of the difficulty to reduce CO_2 emissions is the marginal price of CO_2 (Figure 5). When CCS is available and contributes to the mitigation the marginal price of CO_2 is lower. When CCS is not available, the Iberian Peninsula bubble cannot achieve the target with domestic options only, and emission permits are imported from the RoW in 2050 (Figure 2, left, up) at the cost indicated by the corresponding marginal price of CO_2 (values are slightly lower than the cost of purchasing permits due to terminal discounting conditions in the model). As shown in the same Figure 2 permits from the RoW are imported in 2050 in the HIGH MITIGATION scenario also when CCS is available. The Portuguese and Spanish energy systems contribute to mitigation for the remaining part, according to the results of the high demand scenarios that are reported in [29] (see also [30] and [31]).

In the 'CONSERVATIVE CCS' scenario, which in 2050 has an emission reduction target of -40% compared to 2005, emissions avoided with CCS contribute to mitigation by 50% in the period 2040-2050, the purchase of CDM from Morocco 20%, no/low CO_2 electricity generation technologies about 50%, and compensates the 20% emissions growth in the end use sectors. In the 'HIG MITIGATION' scenario (-80%) emissions avoided with CCS contribute to mitigation by 25% of the emissions in the period 2040-2050, the purchase of CDM from Morocco and permits from the Rest of the World by 30%, no / low CO_2 electricity generation technologies by 30%, and the end use sectors by about 15%.

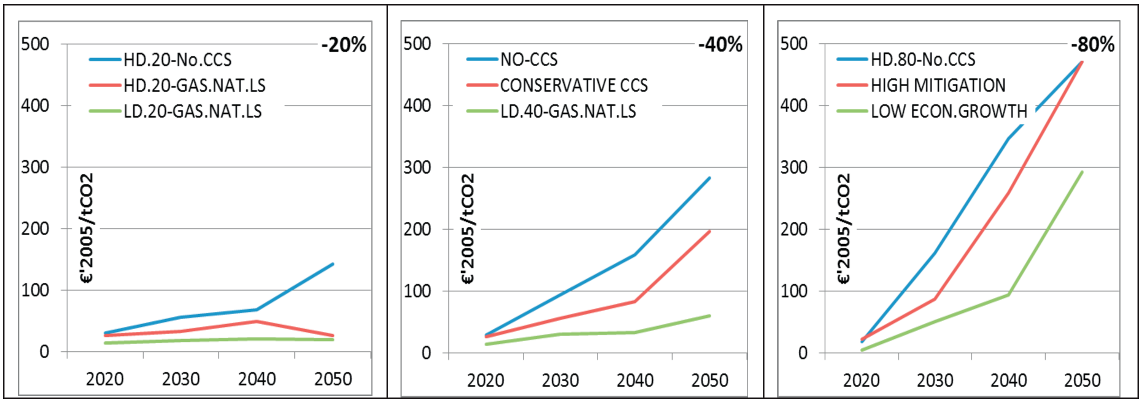

Figure 5: Marginal price of CO_2 by emission reduction target in 2050 (with reference to 2005 emissions)

Although the generation of electricity grows from 2005 to 2050 by 70-90% depending on the scenario, in the Iberian Peninsula the electricity generation sector is the major contributor of energy supply sectors to mitigation in all scenarios, with shares always above 50% after 2020; in the period 2040-2050 the share is over 70% if the mitigation is 40% or more. The electricity generated by fossil fuels contributes too, with efficiency improvements and fuel switching from coal to gas: the unit emission falls from 925 gr CO_2/kWh in 2005 to 420-450 gr CO_2/kWh in the period 2040-50 when the emission reduction target is 40% or more.

The actual contribution to mitigation of end use sectors is much higher than mentioned above, because the demand for energy services almost doubles from 2005 to 2050. The strong decoupling of demands and emissions in the 'HIGH MITIGATION' scenarios is achieved by price-induced demand reductions (20%), energy efficiency improvements (15%) and fuel switching to end use devices using no/low CO_2 fules.

Conclusion

CCS is generally competitive and exploited to its maximum technical potential under wide assumptions about storage potentials and cost, transport routes and costs, capture technologies emissions and costs, cost of the main other mitigation technologies. CCS can play a significant role in the Iberian Peninsula under intermediate and strong mitigation scenarios. With low economic growth assumptions CCS remains competitive but the market is reduced.

Capture potential and pipeline network constraints appear stronger determinants of deployment levels compared to engineering costs and storage potentials.

When the mitigation target becomes more stringent, CCS does not reduce enough; countries are obliged to reduce emissions at the source, and the market for CCS reduces. If CCS is not available, less CO_2 emissions are generated using other more expensive mitigation options and buying expensive permits.

Since the cost difference between the scenarios with free routes and the scenarios with routes following natural gas pipelines is negligible in terms of cost and cumulative storage, it seems that there is room for negotiating socially acceptable infrastructures.

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